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The impact of log-end splits and spring on sawn recovery of 32-year-old plantation *Eucalyptus globulus* Labill.

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Abstract Thirty dominant or co-dominant, straight trees were selected from a 32-year-old thinned plantation of *Eucalyptus globulus* Labill. Growth strain at tree surface at breast height was estimated using a CIRAD-forêt method. Log-end splits in the butt logs were measured. The butt logs were quarter-sawn following a pre-determined sawing pattern. The most common dimensions of sawn boards were $28 \times 105 \times 3000$ and $28 \times 77 \times 3000$ mm. The volume of the curved-edge off-cuts was estimated for each butt log. The end splits in the dried sawn boards were measured and the volume of the wood containing the splits in the boards calculated.

The estimated reduction in sawn recovery due to removing the curved edges in the slabs was equivalent to 6% of the log volume. The estimated reduction in recovery due to end-docking log-end splits was equivalent to 1% of the log volume, or approximately 4% of the dried board volume. For a sawmill processing 40 000 m^3 of logs per annum, this could translate into an annual loss of $ 758 000 (log volume) and $ 385 000 (board volume). These numbers are high in the context that end splits in these logs overall were quite mild and the estimated strain at tree surface was moderate.

Auswirkung von Kernrissen und Längskrümmung auf die Ausbeute von 32-jährigem Plantagen-Eukalyptus (*Eucalyptus globulus* Labill.)

Zusammenfassung Dreißig herrschende bzw. mitherrschende, geradschaftige Stämme wurden auf einer Durchforstungsfläche mit 32-jährigem Eukalyptus (*Eucalyptus globulus* Labill.) ausgewählt. Wachstumsspannungen an der Stammoberfläche in Brusthöhe wurden mittels einer CIRAD-Forst Methode geschätzt. Die Erdstammstücke wurden im Kreuzholzschnitt eingeschnitten, nachdem an diesen die Risse am Hirnholz gemessen worden waren. Die häufigsten Maße der eingeschnittenen Bretter waren $28 \times 105 \times 3000$ mm und $28 \times 77 \times 3000$ mm. Für jeden Erdstammabschnitt wurde das beim Besäumen abgetrennte Holzvolumen geschätzt. In den eingeschnittenen und getrockneten Brettern wurden die vom Hirnholz ausgehenden Risse gemessen und das davon betroffene Holzvolumen errechnet.

Der geschätzte Ausbeuteverlust durch das Besäumen entsprach 6% des Rundholzvolumens. Erforderliche Kürzungen infolge der vom Hirnholz ausgehenden Risse verringerten die Ausbeute um 1% bezogen auf das Rundholzvolumen bzw. etwa um 4% bezogen auf das Volumen der getrockneten Bretter. Für ein Sägewerk mit einer Einschnittkapazität von 40 000 m^3 pro Jahr könnte sich dies in einem jährlichen Verlust von $ 758 000 (Rundholz) und. $ 385 000 (Schnittholz) niederschlagen. Diese Zahlen sind hoch, gemessen an der Tatsache, dass die Rissbildung in den untersuchten Stämmen schwach ausgeprägt und die geschätzten Wachstumsspannungen an der Stammoberfläche mäßig waren.

1 Introduction

Eucalyptus globulus Labill. (Tasmanian blue gum) is the most extensively planted eucalypt species in Australia, approximately 395 000 ha as of June 2002 (NFI 2003). The majority of these plantations have been targeted for wood chip export. However, establishing plantations to produce logs suitable for a wider range of products would provide opportunities for alternative markets.

Of the total blue gum estate in Australia, a substantial area is more than 150 km from the shipping ports, a distance beyond which it is currently considered uneconomic to transport woodchips. In addition, much of the area planted within an economically feasible distance may not be under any contract for sale as woodchips. Development of alternative higher value uses for this timber could be of economic benefit to individual farmers and tree growers, and to the rural community, by increasing income and providing additional employment.

One of the key factors limiting higher-value use of young eucalypts as sawlogs is high growth stress (Malan 1997, Garcia

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1999, Muneri et al. 1999, Waugh 2000, Maree and Malan 2000, Yang et al. 1996, Yang et al. 2002, Yang and Waugh 2001). The release of residual growth stresses results in log-end splitting, flitch moment and further splitting of the log-end splits during sawing, sawn board distortion and thickness variation, and reduced choices of sawing patterns.

Sawn board distortion of various severities has been reported in plantation blue gum (Thomson and Hanks 1990, Brennan et al. 1992, Waugh and Yang 1993, Moore et al. 1996, Northway and Blakemore 1996, Yang and Waugh 1996). A recent study on 59, 10-year-old blue gum trees showed that distortion alone caused up to 40% rejection of sawn boards as feedstock[1], and stem surface strain and log diameter in combination accounted for up to 42% of the total variation in the percentage of excessively distorted boards (Yang et al. 2002).

Utilizing plantation-grown eucalypts for sawn timber is not common in Australia and results of studies have been variable and inconclusive. Whilst the fundamental aspects of split formation and propagation have been investigated by many researchers, as documented in Archer (1986), and more recently by Laghdir (2000) and Jullien et al. (2003), there is only limited knowledge of the loss of sawn timber recovery due to log-end splits and flitch/slab distortion. Also, there is no eucalypt breeding program in Australia for reducing growth stress because little is known about threshold levels of growth stress, the heritability of wood properties that govern growth stress, and the genetic correlations between these properties and other key wood properties.

A study was recently undertaken to quantify the impact of log-end splits and spring in slabs on sawn timber recovery and the use of wood characteristics measured from breast height cores to identify trees prone to excessive sawn board distortion and log-end splitting (Yang and Pongracic 2004).

The results of this study are reported in two separate papers. This paper reports the reduction in sawn recovery due to log-end splitting and the removal of distortion in slabs. The second paper reports relationships of wood properties with log-end splitting and sawn board distortion.

Unless otherwise specified, the terms ‘growth strain’ and ‘growth stress’ respectively refer to the residual longitudinal strain and stress that exist in standing trees or logs.

2 Experimental Method

2.1 Tree selection

Thirty dominant or co-dominant straight trees with good stem form were selected from a 32-year-old thinned plantation of *Eucalyptus globulus* Labill. grown at south of Traralgon in central Gippsland, Victoria. These trees were considered to contain low levels of tension wood and were capable of being sawn in a conventional sawmill (Washusen et al. 2004).

[1] The Australian standard AS2796.1 defines feedstock as sawn and partially processed boards intended for further processing into sawn or milled products, and may be supplied at any moisture content. The spring limit for boards of 40 × 100 × 3600 mm as feedstock is 42 mm.

2.2 Growth strain estimation

Growth strain at breast height was estimated using a CIRAD-forêt method at four circumferential locations corresponding to the North, South, East and West cardinal directions. With the CIRAD-forêt method, a piece of bark (approximately 200 mm long and 100 mm wide) is removed from a standing tree to reveal the fresh wood surface. Using a guide that helps parallel alignment with the stem axis, two notched pins are punched into the wood, and a small indentation is made at the same time at the mid-distance between the two pins. The nominal distance between the two pins is 45 mm. A steel measurement frame that is connected to a digital dial gauge, reading to 0.001 mm resolution, is then hung on the upper pin, with its spring feeler touching the lower pin. The gauge reading is set to zero prior to drilling. A hole of 20 mm in diameter is manually drilled at the small indentation in the radial direction to a depth of 20 mm or until the gauge reading stabilizes. The distance between the two pins, or between the top and bottom edges of the hole, increases in the longitudinal direction if the wood is under tension or decreases if the wood is under compression. The longitudinal displacement between the two pins is displayed by the gauge and recorded.

The angle of spiral grain was observed in the debarked window and visually estimated and recorded.

2.3 Log-end splits

The 30 trees were harvested in April 2003 and stored under water spray at the Black Forest Sawmill in Victoria. The characteristics of log-end splits (split length on the log end and log surface, and split width at the log periphery) were measured for each butt log the day before sawing in June 2003. The length of radii corresponding to the four cardinal directions was also measured on the large end of each butt log.

Previous experience has shown that the split length on the log surface alone was not a useful parameter in describing the negative effect of the splits on sawn recovery. In this study, the severity of log-end splits was described using Split Index 1 (SI-1) and Split Index 2 (SI-2). The SI-1 and SI-2 for a single split were calculated using Eqs. 1 and 2, respectively. In deriving SI-2, the following assumptions were made to simplify the calculation: (1) each split has a split plane inside the log, which has the shape of an isosceles right-angled triangle, regardless of whether the split has extended to the log periphery or not, and (2) when a split propagates from the periphery along the log surface ($SL_{SURFACE} > 0$), the inner split plane also extends the same distance along the log axis (Fig. 1).

$$\text{SI-1-Single} = (SL_{END} + SL_{SURFACE})/R_{MEAN} \quad (1)$$

$$\text{SI-2-Single} = [(SL_{END} \times A/2) + (SL_{SURFACE} + B) \times SL_{END}/2]/R^2_{MEAN} \quad (2)$$

$$= [(SL_{END} \times SL_{END}/2) + (SL_{SURFACE} \times SL_{END})]/R^2_{MEAN} \quad (3)$$

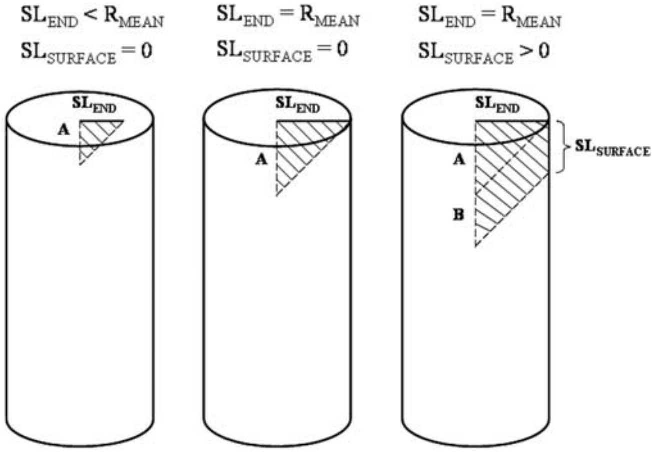

Fig. 1 Illustration of the symbols used in calculating Split Index 2 (SI-2). The shaded area is the inner split plane
Abb. 1 Darstellung der Symbole, die zur Berechnung des Rissindex 2 (SI-2) verwendet wurden. Die schraffierte Fläche stellt die innere Rissebene dar

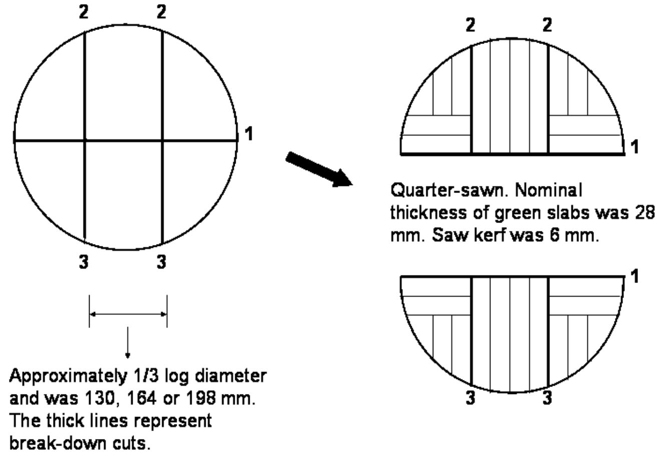

Fig. 2 Outline of the quarter sawing strategy. The numbers refer to the sequence of break-down cuts as shown in thick lines
Abb. 2 Schema des Kreuzholzschnittes. Die Zahlen beziehen sich auf die Reihenfolge der Trennschnitte, die als dicke Linien dargestellt sind

Where:

SL_{END}	=	split length on the log end
$SL_{SURFACE}$	=	split length on the log surface
R_{MEAN}	=	mean radius of the log end
A	=	equal to SL_{END}
B	=	equal to $SL_{SURFACE}$

There is limited knowledge in published literature about the actual shape of the split plane. The actual shape may be quite different from an isosceles right-angled triangle; it may vary between logs and may easily take a three-dimensional shape in the presence of deviated wood grain. Therefore the assumptions for Eqs. 1 and 2 are relatively crude and may be improved in the future.

Neither of the split indices has units since SI-1 was weighted by the mean radius and SI-2 was weighted by the mean radius squared (this weight factor is equivalent to the log cross-sectional area while π is a constant).

The split indices can also be calculated for a log end. SI-1-LogEnd equates to the sum of all SI-1-Single values at a log end. Similarly, SI-2-LogEnd equates to the sum of all SI-2-Single values at a log end. One advantage of SI-1-LogEnd and SI-2-LogEnd is that they reflect the overall splitting severity of a log end, therefore are more adequate for data analysis.

2.4 Sawing

The logs were quarter-sawn at the Black Forest Sawmill. The sawing strategy, as outlined in Fig. 2, was to break down the log into two halves and break each half into three flitches using a twin edger, quarter-saw the flitches into 28-mm-thick slabs at a two-man, re-saw bench (a circular saw), and size the slabs to width using a multi-saw re-saw. Some of the slabs were sawn to width at the two-man bench. The nominal thickness and length of the green boards were 28 mm and 3000 mm; the widths varied among 57 mm, 77 mm, 105 mm, 140 mm, and 163 mm. The most common widths were 77 mm and 105 mm.

A reduction in sawn recovery occurs at several processing stages. Whereas saw kerf is a major source of the loss, this study dealt only with sizing cuts that remove the curved edges in green slabs and end-docking[2] that removes end splits in the dried boards.

2.5 Measurement of the volume of the curved-edge off-cuts

For safety reason, green slabs cannot be accessed during sawing. Rather than measuring the distortion in slabs directly, the impact of distortion in slabs on sawn recovery was instead assessed indirectly by estimating the volume of the curved-edge off-cuts as explained below.

The re-saw process turned slabs into boards. This process usually yielded two curved-edge off-cuts from each slab, which often differed in size and shape. The two simplest situations are illustrated in Fig. 3. In one situation, only one board was cut from a slab (Fig. 3a); in the second situation, two boards of different widths were cut from a slab (Fig. 3b).

The off-cut A (Fig. 3a,b) typically had one curved edge, one nominal straight edge, and a thickness similar to the board (28 mm in this case). This piece can be further divided into two components, the curved-edge component (A1 in Fig. 3c) and the straight-edge component (A2 in Fig. 3c). A2 was the extra wood that was sawn off at the same time as A1 in order to give the board a common width, and it was kept as small as possible. The volume of the off-cut A was generally larger than the volume of the off-cut B, but not significantly.

Most of the curved-edge off-cuts from the convex side (A in Fig. 3a,b) were recovered during sawing. The maximum width of each off-cut (H in Fig. 3c) was measured after sawing. The re-

[2] It is assumed that end docking was applied at a later processing stage to remove end splits in the dried boards.

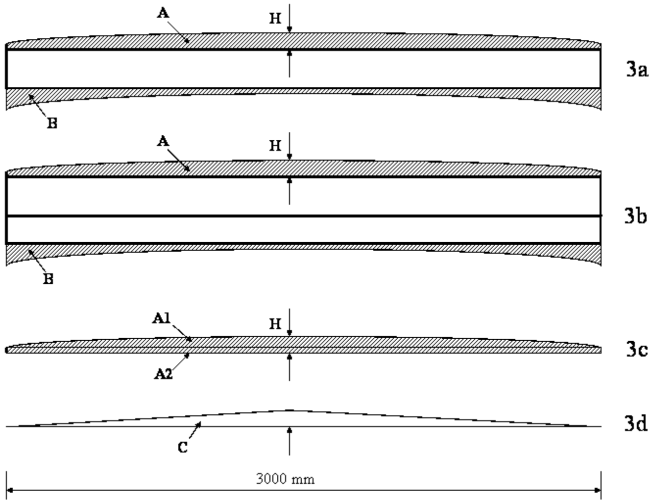

Fig. 3 Illustration of off-cut pieces (the shaded area A and B) from two slabs of different widths in two simple re-saw situations and how to estimate the volume of these off-cuts by approximating a curved-edge object as a triangle-shaped object (C). H is the point of maximum width
Abb. 3 Darstellung der durch Besäumen wegfallenden Holzteile (schraffierte Flächen A und B) zweier Brettrohlinge mit unterschiedlicher Breite bei einfachem Nachschnitt. Abschätzung des Volumens der wegfallenden Holzmenge durch näherungsweisen Ansatz einer dreieckförmigen Fläche (C). H ist die Stelle der größten Breite

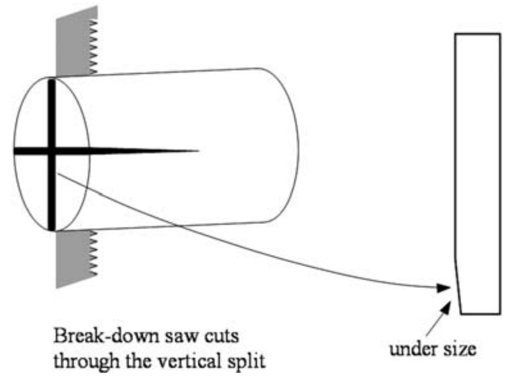

Fig. 4 Illustration of a flitch under size at one end that is associated with a wide log-end split
Abb. 4 Darstellung der Untermaßigkeit eines Brettrohlings durch einen breiten, vom Hirnholz ausgehenden Riss

maining spring in sawn boards was measured at the green chain during sawing.

The volume of the curved-edge off-cuts per slab was estimated under two assumptions: (1) the sizing cuts took place on both sides of a slab and the two off-cuts A and B were of equal volume, and (2) each off-cut was approximately a triangle-shaped object (object C in Fig. 3d). The approximate volume of a curved-edge off-cut can then be calculated from the height of the triangle (H) and the length and thickness of the board (3000 mm and 28 mm, respectively) using Eq. 4. The approximate volume of the two curved-edge off-cuts per slab was twice the volume of the triangle-shaped object (off-cuts A plus B).

$$\text{Volume of one off-cut} = \text{length (3000 mm)} \times \text{height (H)}/2 \times \text{thickness (28 mm)} \quad (4)$$

2.6 Measurement of spring and end splits in dried boards

Spring was measured (AS2796.1) after drying. The proportion of dried boards that exceeded 10 mm spring[3] was calculated for each log as the number of dried boards exceeding 10 mm limit divided by the total number of dried boards from that log, expressed as a percentage. This expression not only reflects the severity of board distortion but also has a practical meaning to sawmills to assist them in identifying the source of lost sawn recovery and lost productivity. Bow was not measured before and after drying because it was small.

Some green sawn boards will inevitably contain end splits when the initial log-end splits cannot be avoided during sawing. These splits may become longer during drying. The length of an end split in a dried board thus equals the length of the initial log-end split plus the length of the new extension during drying. The volume of the lost wood due to log-end splits will be over-estimated if any split in dried boards is used to determine the volume of the lost wood. Another potential source of over-estimation is associated with the sawing system that cut these logs. The twin-saw edger at this mill uses two “dogs” to hold and position the logs in log breakdown, which may have initiated new splits or worsened the existing splits. To prevent over-estimation, only the initial log-end splits that were present in the dried boards were measured. These splits were quite easy to recognise as they were still covered with dry mud or stained with soiled water.

It was assumed that the dried boards would be end-docked to remove the end splits and cut to commercial lengths simultaneously. The volume of the docked ends per board was equal to the total effective length of the splits in that board multiplied by the cross-sectional area of that board. The proportion of end-docking was calculated for each log in two different ways: the volume of the docked ends of the dried boards divided by the log volume, and the volume of the docked ends of the dried boards divided by the volume of all dried boards from that log. The presence of wide splits can complicate this calculation. When a single-saw system is used to cut a log containing wide splits, the sawyer tends to cut through the major split (the saw line is parallel with the splits, Fig. 4). The flitch on each side of the saw would be under size at its end (Fig. 4) and, therefore, the potential effect of a wide split on sawn recovery would be twice as much as that of narrow splits. This situation was rare in this study as the log-end splits were less than 6 mm wide.

[3] In assessing board distortion, the spring limit of 10 mm was adopted from the CSIRO Forestry and Forest Products grading criteria for appearance products of 100 mm wide and 3000 mm long. These grading criteria were very similar to the current Australian Standard for hardwood sawn and milled products (AS2796.1) but defined the limit for each type of defect more precisely.

3 Results and discussion

3.1 General observations on the trees

The mean diameter at breast height over bark (DBHOB) was 461 mm, and ranged from 372 to 580 mm. Eleven trees showed noticeable spiral grain of up to 20° at the stem surface. Spiral grain was observed in at least one debarked window in every tree, and was seen in all four debarked windows of one tree. Almost every butt log had a much longer radius at the West side and, consequently, a much shorter radius at the East side (Table 1). The difference in growth ring width between the West and East sides was much greater near the pith, indicating that the eccentric growth occurred at greater pace when the trees were young.

3.2 Log-end splits

Log-end splits were not severe overall and appeared as small cracks about 1 to 2 mm wide on the large ends of most logs. In 16 logs the splits on the log surface next to the large log ends were wide enough to be observed. No log surface splits were observed next to the small log ends. Severe end splits, where the split width was 3 mm or more and the total split length on the log surface was greater than 400 mm, were present in only two logs. The extent of the splits on the log surface could not be accurately determined with the naked eye because of mud substantially filling the splits. The overall low level of end splitting may be attributed to the frequent presence of interlocked grain in blue gum (Bootle 1983) by comparison with other species such as *E. regnans*, with which more fracture energy is required to split the wood.

The small log ends had noticeably fewer splits, which appeared as fine cracks. End splits on the small log ends were therefore recorded as zero. Splits on the small log end were rarely aligned with those on the large log end, as frequently observed in logs of other eucalypt species that are quite different from *E. globulus*. This may be explained by likely differences in wood properties and residual stresses between the log ends.

Overall, wide splits (3 mm and above) were longer along the log axis. However, this relationship was not as consistent for narrower splits. A reliable relationship between split width on the log ends and split length on the log surface would be very useful for prediction in log quality assessment as the split width is easily measured on the log ends. However, this could not be developed here, partly because the data set was skewed towards zero.

Table 1 Mean values of radius length and the longitudinal displacement at each cardinal direction ($n = 30$)
Tabelle 1 Mittelwerte der Stammradien und der Längsabweichung in den Haupthimmelsrichtungen ($n = 30$)

Properties	North	East	South	West	Mean
Mean radius (mm)	204	197	207	257	216
Mean radius / DBHOB (%)	50	43	45	56	47
Mean displacement (mm)	0.094	0.087	0.088	0.103	0.093

3.3 Spring and end splits in sawn boards

Of the total 503 boards, 26% (129 boards) showed various amounts of spring in the green state, mostly below 10 mm but higher for 15 boards (Table 2).

Spring not only increased in these 129 boards during drying but also formed in other originally straight boards. The average increase was 5 mm but severe in some boards (e.g. spring > 35 mm). The maximum increase in spring in a single board was 37 mm. Most boards sprang in the same direction during drying as when they were green but seven boards sprang in the opposite direction. Only 6 boards remained straight during drying. Spring measured after drying is the initial spring due to the release of growth stress plus the distortion caused by differential longitudinal shrinkage during drying (Kliger et al. 1996). It was found that spring before and after drying was not significantly correlated.

It was found that every log, except one, yielded dried boards with greater than 10 mm spring. The mean percentage of dried boards exceeding 10 mm spring for the 30 logs was 43% and reached 88% for one log (Table 2).

Generally, dried boards need to be trimmed to appropriate sizes and to remove excessive spring to make saleable wood products at a later stage. Clearly, the recovery and value of the final sawn products will be affected by the magnitude of spring before trimming. This was not determined here but should form the bases for future studies.

There was no apparent link between spring in the dried boards and the spiral grain observed on the log surface. However, it was found that large distortion would result if both high surface strain (the longitudinal displacement) and severe spiral grain were present. For example, the log that had the highest percentage of boards with greater than 10 mm spring had an average longitudinal displacement of 0.129 mm and spiral grain of 20° on two opposite sides of the log. This log had a smaller DBHOB of 379 mm, which could have also contributed to the large spring, as the longitudinal strain inside a smaller-diameter tree in general follows a steeper distribution along the tree radius (Jacobs 1938, Kuebler 1959).

Forty-seven percent of the dried boards had end splits. The longest end split was 810 mm and the average length was

Table 2 Data for spring and loss of recovery due to sizing cuts and docking of end splits
Tabelle 2 Längskrümmung und Ausbeuteverlust durch Besäumen und Kürzen infolge Rissbildung

Measurements	Mean	SD	Range
Spring in green boards (mm)	6	4	2–20
Spring in dried boards (mm)	11	7	0–40
Boards with spring > 10 mm (%)	43.0	23.6	0–87.5
Width of curved-edge off-cuts (mm)	24	13	5–82
Volume of curved-edge off-cuts per log (%)	6.0	1.9	1.1–9.6
Volume of end docking per pre-docking board volume (%)	3.76	3.02	0.7–13.5
Volume of end docking per log (%)	0.97	0.76	0.2–2.9

165 mm. End splits in the dried boards are a combination of initial log-end splits and their likely extension during drying in response to differential longitudinal shrinkage across the boards.

3.4 Reduction in sawn recovery due to removal of curved edges and end splits

Approximately 4% of the dried board volume would be lost as a result of end docking (Table 2). If the volume recovery of dried sawn product is 26%, then for an average log of 0.38 m^3 (200 mm radius and 3000 mm length), the lost volume due to end docking would be 0.004 m^3 (0.38 $m^3 \times 26\% \times 4\%$). At an average price of \$ 914/m^3 for dried sawn product, the value of the lost product is \$ 3.66 (\$ 914×0.004 m^3) per log or \$ 9.63 per cubic metre of logs.

The reduction in sawn recovery due to removal of the curved edges in slabs per log was calculated as the volume of the curved-edge off-cuts divided by the log volume and multiplied by 100. The average loss was found to be 6% for the 30 logs (Table 2) and reached over 8% for five logs. If the volume recovery of green sawn boards is 38% and the volume loss of the curved-edge off-cuts is 6%, then for an average log of 0.38 m^3 (200 mm radius and 3000 mm length), the green recovery would drop by 0.02 m^3 (0.06×0.38 m^3). At an average price of \$ 360/m^3 for green sawn timber, the value of the lost recovery is \$ 7.20 (\$ 360×0.02 m^3) per log or \$ 18.95 per cubic metre of logs. While this value seems low on a log basis, a mill must also consider that the costs of removing the curved edges may have a significant effect on the efficiency of the mill. The 6% loss of log volume is partially associated with the quarter-sawn strategy and may be reduced if the logs were back-sawn. On the other hand, the loss could have been higher if a normal log sample from this plantation was used in this study. Also, the removal of spring in the dried boards would incur additional loss of wood and loss of productivity.

The above analysis shows that the loss in product value at \$ 18.95/m^3 due to sizing cuts is almost twice the loss in product value at \$ 9.63/m^3 due to log-end splitting. While neither the end split loss nor the curved-edge off-cut loss will ever be entirely eliminated, it may be worthwhile for a mill owner to have an indication of the extent of the loss, via a wood quality index, in order to better negotiate log prices.

3.5 Relationship between longitudinal displacement, log-end splits and loss of sawn recovery

Significant and positive correlations were found between the volume of end docking (as a percentage of log volume) and SI-1-LogEnd ($R^2 = 0.31$, $p < 0.01$) and SI-2-LogEnd ($R^2 = 0.32$, $p < 0.01$). The moderate strength of these correlations was more or less expected because the volume of end-docking will also be affected by log size, sawing strategy and board dimensions, which determine how likely the log-end splits can be prevented from occurring in sawn boards. Once a board is cut, the cross-sectional area of the board will determine the volume of end docking for a given length of end split; the smaller the cross-sectional area, the less the volume of end docking. The SI-1-LogEnd and SI-2-LogEnd were positively and significantly correlated with the mean longitudinal displacement per log ($R^2 = 0.25$ and 0.28, respectively). The R^2 values would be improved to 0.33 and 0.36 respectively if the displacement was multiplied by DBHOB. However, the volume of end docking was not related to the longitudinal displacement.

The volume of the curved-edge off-cuts was not significantly correlated with the longitudinal displacement. This indicates that the distortion of flitches and slabs at the release of growth stress during sawing is a complex matter. Despite the lack of correlation, the release of growth stress remains to be the most important cause of distortion in flitches, slabs and green boards (Jacobs 1938, Boyd 1950). To understand how flitches and slabs move during sawing and how the movement is linked to growth stress and strain, sophisticated stain measurement system and mechanical modelling will be needed.

There was no significant relationship between the volume of the curved-edge off-cuts and log-end split indices. This was not surprising as the split indices are indicators of the overall split severity of the log ends, whereas the volume of the curved-edge off-cuts is an indirect measure of spring in slabs. Log-end splits and spring in slabs are both fundamentally linked to growth stress but their formation and magnitude also depend on other factors such as green wood toughness corresponding to a rupture in mode I of the radial-longitudinal plane and rigidity components in respect of log-end splits (Jullien et al. 2003) and the gradient of longitudinal modulus in radial direction in respect of spring.

4 Conclusions

Log-end splits were not severe overall and occurred more often in the large ends of the logs. New and simple split indices that incorporate split depth along the log axis were developed to quantify the overall severity of log-end splitting. The estimated reduction in sawn recovery due to end docking to remove end splits in the dried boards was equivalent to 1% of the log volume, or approximately 4% of the dried board volume. This equates to \$ 3.66 in lost dried product for an average log of 0.38 m^3 (200 mm radius and 3000 mm length), or \$ 9.63 per cubic metre of logs if log volume recovery of dried sawn product is 26% and the average price of dried sawn timber is \$ 914/ m^3. For a mill processing 40 000 m^3 per annum, the lost product value would be \$ 385 000 per annum.

The reduction in green sawn recovery associated with flitch or slab distortion was estimated based on the volume of the curved-edge off-cuts removed from the slabs. The estimated loss of green sawn recovery was equivalent to 6% of the log volume. This equates to \$ 7.20 in lost green product for an average log of 0.38 m^3 (200 mm radius and 3000 mm length), or \$ 18.95 per cubic metre of logs if log volume recovery of green sawn product is 38% and an average price of green sawn timber is \$ 360/m^3. For a mill processing 40 000 m^3 per annum, this loss would be \$ 758 000 per annum.

The annual combined effect of log-end splits and the curved-edge off-cuts on a 40 000 m^3 per annum sawmill would be over \$ 1 million. This figure needs to be viewed in the context of quarter-sawn strategy and relatively low tension wood occurrence in the study logs. Understanding the impact of log quality on sawmill profit should assist the processing industry to assess whether it is overpaying when purchasing logs.

Spring increased by an average of 5 mm during drying and reached over 10 mm in a number of the dried boards. If 10 mm were set as the spring limit, then 43% of the dried boards would have exceeded this limit and would need shortening or sizing cuts at a later stage to reduce or remove the excessive spring. This would incur further loss of wood and productivity.

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